AFRL-AFOSR-JP-TR-2016-0085

Flow Visualization of a Rotating Detonation Engine

Toshiharu Mizukaki
TOKAI UNIVERSITY

10/05/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
17-10-2016	Final	05 Sep 2014 to 04 Dec 2015

4. TITLE AND SUBTITLE
Flow Visualization of a Rotating Detonation Engine

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA2386-14-1-0012

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Toshiharu Mizukaki

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TOKAI UNIVERSITY
4-1-1, KITAKANAME, HIRATSUKA
KANAGAWA, 259-1292 JP

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AOARD
UNIT 45002
APO AP 96338-5002

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR IOA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-JP-TR-2016-0085

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The rotating detonation engine (RDE) is a propulsion system that obtains thrust using continuously existing detonation waves. A rotating detonation combustor (RDC) usually has an annular shape that allows detonation waves to propagate in the circumferential direction. In this study, we used a disk-shaped RDC with a combustion chamber with flat-plane glass walls to observe the structure of the phenomena. Self-luminescence, shadowgraphs and schlieren visualization experiments were performed and compared. Results revealed that detonation waves were propagating in a mixture layer of 3 gases, fuel, oxidizer and burned gas at 1,600 to 900 m/s; CJ velocity was 2,376 m/s. Waves maintained a three-dimensional complicated wave shape in the disk-shaped combustion chamber with parallel-jet injectors.

15. SUBJECT TERMS
Combustion and Dentonation, Pressure Gain Combustion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR	11	KNOPP, JEREMY

19b. TELEPHONE NUMBER *(Include area code)*
315-227-7006

Final Report for AOARD Grant 134062-141OA109 "Flow Visualization of a Rotating Detonation Engine"

Date 3/4/2016

PI and Co-PI information:

Name of Principal Investigator; Toshiharu Mizukaki
e-mail address; mizukaki@keyaki.cc.u-tokai.ac.jp
Institution; Tokai University
Department; Department of Aeronautics and Astronautics
Mailing Address; 4-1-1, Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan
Phone/Fax; +81-463-58-1211

Period of Performance: 9/5/2014 – 12/4/2015

Summary:

The rotating detonation engine (RDE) is a propulsion system that obtains thrust using continuously existing detonation waves. A rotating detonation combustor (RDC) usually has an annular shape that allows detonation waves to propagate in the circumferential direction. In this study, we used a disk-shaped RDC with a combustion chamber with flat-plane glass walls to observe the structure of the phenomena. Self-luminescence, shadowgraphs and schlieren visualization experiments were performed and compared. Results revealed that detonation waves were propagating in a mixture layer of 3 gases, fuel, oxidizer and burned gas at 1,600 to 900 m/s; CJ velocity was 2,376 m/s. Waves maintained a three-dimensional complicated wave shape in the disk-shaped combustion chamber with parallel-jet injectors.

Introduction:

A detonation wave is a self-sustained combustion wave that propagates at supersonic speed. Because of the supersonic propagation, the detonation wave compresses the reactive mixture behind the front shock wave and produces a chemical reaction. This reaction creates high-pressure and high-temperature burned gas. The burned gas then expands and sustains the propagating shock wave. Due to the interaction between the front shock wave and burned gas, the detonation wave can maintain its structure.

Studies have been conducted on rotating detonation engines (RDE) that obtain thrust from the continuously propagating detonation waves in the combustor, mainly for propulsion systems. RDEs have the potential to be simpler and lighter than conventional aircraft and spacecraft, because the detonation cycle theoretically has a higher thermal efficiency. On the other hand, pulse detonation engines (PDE) that obtain thrust by intermittent detonation waves have also been studied, and the performance characteristics of PDEs have been comparatively well clarified. RDEs have a higher thrust density than PDEs, and usually a larger applied mass flow rate; PDEs, however, are easier to control and take a smaller thrust. Based on their features, one can think of RDEs as suitable for next-generation spacecraft/aircraft main thrusters, while PDEs are suitable for reaction control systems because of their greater operability.

In the combustion chamber of a rotating detonation combustor (RDC), fuel and oxidizer must be mixed very quickly, because detonation waves propagate in the combustion chamber at high frequency. Therefore, the phenomena of combustion and gas dynamics are complicated and difficult to elucidate. Several studies have been conducted on the structure of detonation waves in RDCs or similar systems. Bykovskii et al. performed a visualization experiment using

disk-shaped RDCs. The researchers were able to view reactions inside the RDC through narrow radial windows. They observed continuously propagating detonation waves in the disk-shaped RDC using a fuel-air mixture, and proposed the basic flow structure in the combustion chamber. Nakayama et al., Kudo et al., and Sugiyama et al. all studied the structure of detonation waves propagating at rectangular-cross-section curved channels to obtain fundamental knowledge about RDCs. It is important to extend this research toward understanding the structure of rotating detonation waves in RDCs with studies as to their application and control performance. Although there have been many such visualization experiments, the structure of detonation waves in RDCs has not yet been fully clarified due to the complexity of the phenomena and difficulty of visualizing the defined area.

In this study, we used a disk-shaped RDC with a two-dimensional (2-D) combustion chamber to obtain more detailed knowledge regarding the phenomena of combustion and gas dynamics in order to control the output of the combustor towards practice. Fig. 1 includes the schematic for an annular RDC (a) and disk-shaped RDC (b). The illustrations are sectional views that include the axis of symmetry. One can consider the disk-shaped RDC used here to be more general than the annular one, because phenomena in the disk-shaped RDC can occur only two-dimensionally, while those in annular RDCs occur three-dimensionally. Therefore, the disk-shaped RDC makes it easier to consider the interaction between plural detonation waves and the RDC structure. This is why we chose the present shape for our basic RDC research. As may be seen in the figure, both sides of the combustion chamber in the disk-shaped RDC are made of glass. This allowed us to observe the inside of the combustor using the schlieren-imaging method. With this apparatus and method, we were able to clarify how the detonation wave was maintained in the mixture layer of fuel, oxidizer, and burned gas.

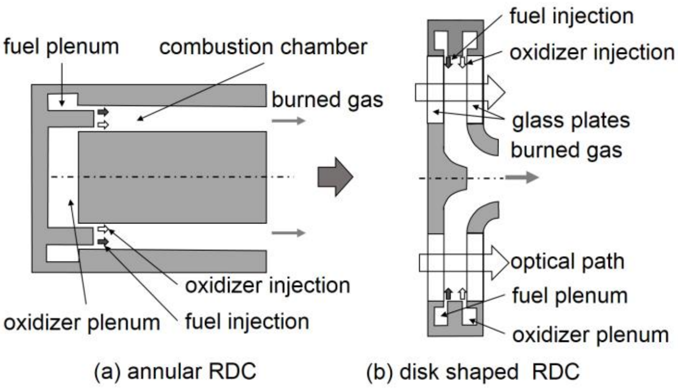

Fig. 1 Schematic of an annular RDC (a), and disk-shaped RDC (b)

Experiment:

1. Disk-shaped RDC

The schematics in Fig. 2 show a side-sectional view of the disk-shaped RDC (2[a]), an enlarged view of the same perspective (2[b]), and a 3-dimensional (3-D) view around the injectors (2[c]). In this study, ethylene and oxygen were used as propellants. These gases were fed to plenums from high-pressure tanks through orifices installed to create an initial choked flow immediately downstream of the tanks. The gases were then injected into the glass-walled combustion chamber through 1-mm slits and injectors shaped in semicircular grooves. Each oxygen injector had a 1.0-mm radius; the ethylene injectors had a 0.8-mm radius. A total of 100 sets of injectors were installed at even intervals. The gases were injected into the combustion chamber in parallel to allow them to mix. The operation began with a detonation wave from the initiator, which was a simple detonation tube attached to the combustion chamber. The

combustion chamber was 5-mm wide and had a 130-mm outer diameter. The visible section also had a 130-mm outer diameter and 75-mm inner diameter. Thus, the injection, mixing, and combustion processes could be visualized simultaneously using the schlieren imaging method.

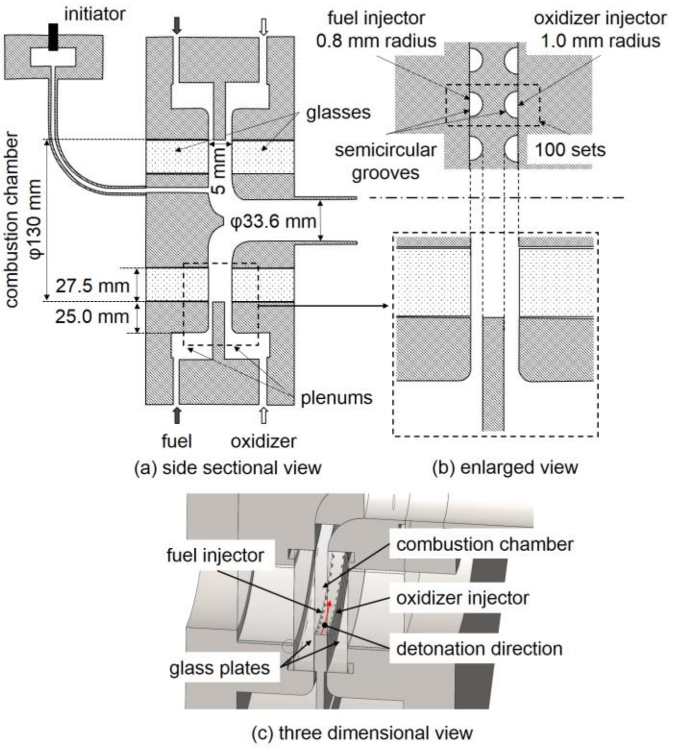

Fig. 2 (a) Schematic of side-sectional view of the disk-shaped RDC; (b) an enlarged view around the injectors; and (c) a 3-D view of the injectors

2. Three types of visualization experiments

The three types of visualization experiments performed to elucidate phenomena in the RDC are illustrated in Fig. 3. The figure shows schematics for the: (a) self-luminescence; (b) shadowgraph; and (c) schlieren visualization experiments.

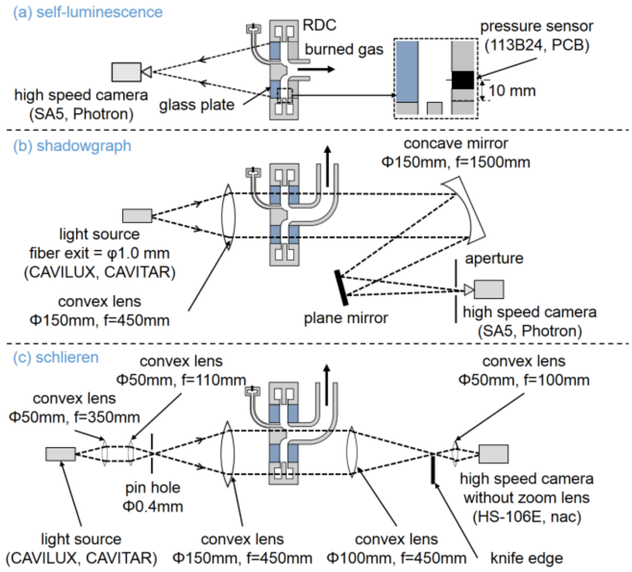

Fig. 3 Schematics of (a) self-luminescence; (b) shadowgraph; and (c) schlieren visualization experiments

In the self-luminescence visualization experiment (Fig. 3[a]) the system was simple, requiring only the RDC and a high-speed camera (SA5, Photron). The framing speed and exposure duration were 150,000-fps and 2.01-μs, respectively. In this experiment, only one side of the combustion chamber was made of glass, while the other side was stainless steel. A high-speed camera with a zoom lens was set behind the RDC to record self-luminescence due to combustion. A pressure sensor (113B24, PCB) was installed on the other side of the wall. It was positioned 10-mm from the outer edge of the combustion chamber. Silicon grease was used to protect the sensor from heat, and this probably led to some delay in output. Specifications for the pressure sensor stated that its rise time was below 0.1-μs, and that it had a pressure resolution of 0.035 kPa. In this experiment, pressure was sampled at 5.0-MHz.

The shadowgraph visualization experiment (Fig. 3[b]) used a convex lens and concave mirror with a diameter larger than that of the combustion chamber to create the test section. Therefore, the greater part of the combustion chamber could be visualized in this experiment. The framing speed was 75,000-fps. A pulse-type light source triggered so that it was perfectly synchronized with the camera was used in order to reduce the exposure time of images. A 20-ns exposure time was selected. The fiber-exit diameter, which determined the sensitivity of the optical system, had a 1.0-mm aperture, and was installed in front of the high-speed camera to reduce self-luminescence from the images. Burned gas was discharged through an exhaust manifold bent at 90º.

Fig. 3(c) is a schematic of a schlieren-imaging visualization experiment. In this experiment, the high-speed camera took images of the combustion chamber locally in order to obtain higher spatial resolution. In addition, a different high-speed camera was used to take higher time-resolution video. The framing speed was 300,000-fps. The pulse-type light source was used again here. The pinhole size was 0.4-mm in diameter, which was smaller than the fiber-exit size of the light source. Exposure time determined by the light source was again 20 ns.

Fig. 4 is a photograph of the RDC used in this study. The RDC was connected to an exhaust chamber through a manifold bent at 90º. As may be seen in the figure, glass plates were installed as combustion chamber walls in order to observe the reactions inside it.

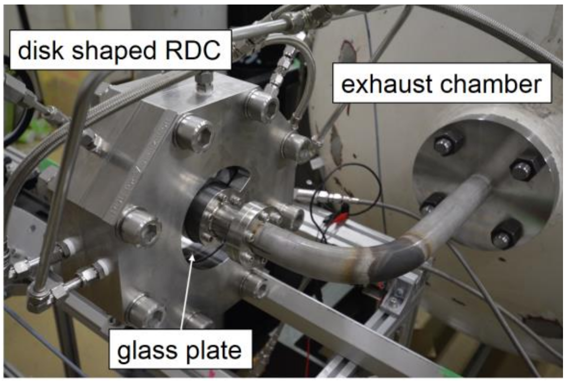

Fig. 4 Photograph of the disk-shaped RDC in the shadowgraph optical system

3. Definition of Mass Flow Rate and Equivalence Ratio

In this experimental system, mass flow rate was controlled by orifices downstream of the high-pressure tanks. Therefore, mass flow rate was approximately constant for short durations, because the pressure in the tank almost never changed. On the other hand, the flow was also choked at the injectors before ignition because the pressure in the plenums was sufficiently higher than atmospheric pressure. The mass flow rate could thus be calculated using the time-averaged plenum pressure before ignition and the geometry of the injector. The following

equation was used to determine the mass flow rate.

$$\dot{m} = \frac{p_{ple} A_{inj}}{\sqrt{RT_0}} \sqrt{\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} .$$

Meanwhile, the equivalence ratio was defined as

$$ER = \frac{\left(\dot{m}_f \middle/ \dot{m}_{ox} \right)}{\left(\dot{m}_f \middle/ \dot{m}_{ox} \right)_{st}} .$$

Results and Discussion:

1. Structure of the Phenomena in the Disk-Shaped RDC

Fig. 5 is a schematic of the structure of the flow phenomena in the disk-shaped RDC proposed in this study. Larger and smaller circles show the outer edge of the combustion chamber and the inner boundary of the visible area, respectively. Continuous lines within the combustion chamber were drawn based on images from the experiments. The dashed lines around the outside of the combustion chamber indicate the injectors. The detonation wave was initiated in region 1 and propagated counterclockwise. Region 2, behind the detonation wave, was filled with high-pressure, high-temperature burned gas. This high-pressure burned gas stopped the injection of ethylene and oxygen and flow back into the injector in the open burning (OB) direction As a result, one contact surface was generated in the injectors between the burned gas and the fuel, and another between the burned gas and the oxidizer. When the local combustion chamber pressure began to decrease, only oxygen was re-injected in the OC direction. After region 3 was filled with oxygen, ethylene was re-injected in the OD direction. The reason for the phase lag between ethylene and oxygen re-injection was that plenums for the two gases were considered to have a pressure difference. Details of this are given below in the discussion of Fig. 7. A well-mixed area developed between the fresh oxygen and ethylene, and became the medium of the next-cycle detonation wave. Since ethylene and oxygen re-injection had a phase lag, as mentioned above, and yet were injected in parallel, a certain distance was needed for them to mix sufficiently. Consequently, the well-mixed area remained a certain distance from the outer edge of the combustion chamber. The detonation wave was likewise propagated at this distance from the outer edge of the combustion chamber.

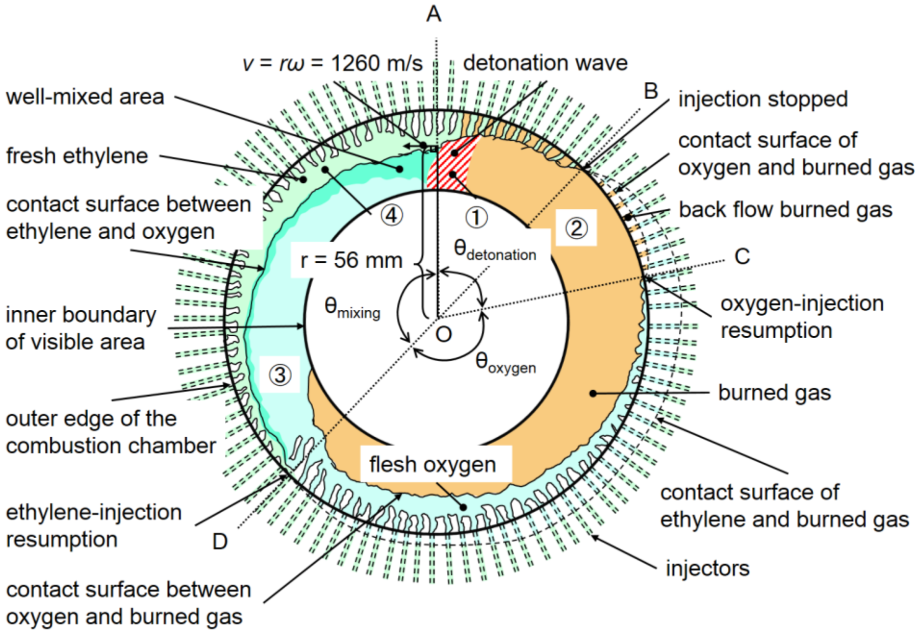

Fig. 5 Schematic of the phenomena in the disk-shaped RDC

As mentioned in Experiment section, the orifices were set upstream of the plenums, which made mass flow rate constant because of the choked flow and almost constant pressure of the feed tanks. We think the mass flow rate to the combustion chamber was therefore also constant, although local chamber pressure became higher than plenum pressure. However, it is possible that mass flow rate to the chamber periodically oscillated or changed extremely briefly and almost instantaneously because of the detonation waves in the chamber. The plenum pressure histories were obtained at only 50 kHz, while the chamber pressure history was recorded at 5.0 MHz. It was thus possible that the plenum pressure oscillated at a higher frequency than the sampling rate of 50 kHz.

The velocity range of the waves was supersonic (we discuss this further below) and the pressure of rear of the waves was greater than the pressure in front of the waves (in the typical pressure-volume diagram of one-dimensional steady-state flow analysis, this solution is defined as “detonation”). Additionally, the waves demonstrated sustained self-propagation. Therefore, they can be considered detonation waves. However, we think that these detonation waves were perhaps different from conventional detonation waves in that they included some complex structures in terms of the wave front and mixing process, local large curvature wave front, or lower heat release than the typical C-J value due to non-perfect mixing.

2. Visualization of Detonation Wave

Fig. 6 shows the self-luminescence visualization experiment from the high-speed camera. Fig. 6(a) is a representative image. The dashed line in the image shows the boundary of the visible area, while the hatched area on the right side of the image represents a supporting structure (i.e., it was impossible to view this area). The luminescence on the upper side of the image was a detonation wave propagating rotationally (note that the circle-shaped luminescence on the bottom of the circle was caused by the grease on the pressure sensor). Fig. 6(b) is a frame from a video taken between 39.17–39.65 ms after the ignition. The framing speed was 150,000 fps and the playing speed was 30 fps. Fig. 6(c) shows continuous images taken from the self-luminescence visualization experiment. The first image was taken 39.17 ms after ignition,

and subsequent images were taken at 13.33-μs intervals. As shown in Fig. 6(c), the luminescence of the detonation wave rotated from the 2-o'clock position in image 1 all the way around by image 20. In images 1-13, the shape of the luminescence maintained a forward tilt, like that in Fig. 6(a). These results suggest that the detonation wave propagated while maintaining a distance from the outer edge of the combustion chamber. In other words, in the configuration of this RDC, the detonation waves required some distance to propagate rotationally because of the mixing process.

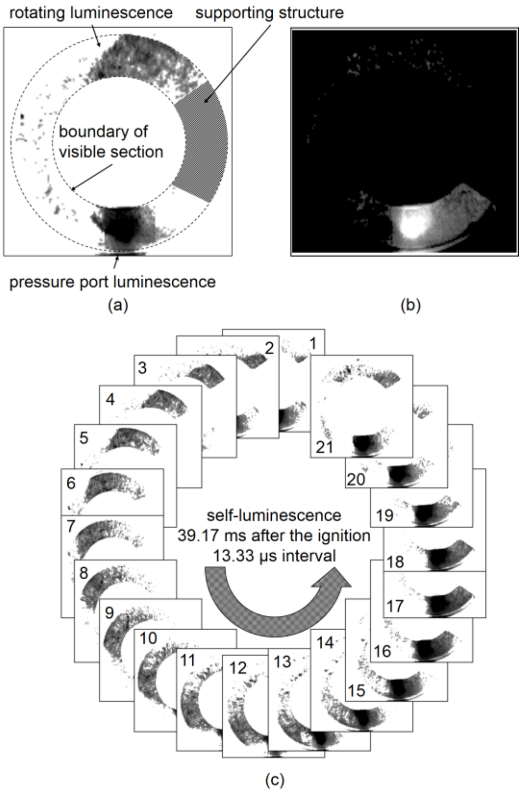

Fig. 6 Individual image (a), video frame (b), and continuous images (c) from the self-luminescence visualization experiment

(Total mass flow rate was 0.25 kg/s and equivalence ratio was 1.6)

Note: images and movie in the figure are inverted right to left in order to make them compatible with the other two types of visualization experiments.

Fig. 7 shows the averaged pressure history of the ethylene and oxygen plenums (a), and the combustion chamber and velocity profile (b). In Fig. 7(b), the crosses and filled diamonds indicate the velocity from the high-speed camera, and the circles show the pressure sensor measurements. The velocity from the camera was calculated as a product of angular velocity and the radius of the outer edge of the combustion chamber. On the other hand, the velocity from the pressure sensor was calculated using an FFT analysis. As shown in Fig. 7(a), there was a 0.1-MPa pressure difference between the ethylene and oxygen plenums before ignition. However, between 10–40 ms, there was hardly any difference. Mass flow rate from upstream of the plenums was constant. Therefore, the effective injection area was decreased due to the increase in pressure. The difference in the ethylene plenum pressure before and after ignition was higher than that of the oxygen plenum. Thus, more ethylene injectors stopped injection than oxygen

injectors. This was thought to be the reason for phase lag between ethylene and oxygen injection seen in Fig. 5. In Fig. 7(b), the velocity measurements from the movie and pressure sensor were in good accord, and the magnitude of the velocity decreased from 1,600 m/s to 900 m/s smoothly. In addition, although the direction of rotation was observed to change twice, the magnitude of the velocity decreased smoothly. From these results, it is thought that the propagation velocity decreased for the following reasons: (1) a mixing shortage due to the decrease of plenum pressure or mass flow rate; (2) an increase in the curvature of the detonation wave; and (3) an increase in the amount of burned gas engulfed by the detonation wave. Fig. 7 shows that when the rotation direction changed, the oxidizer plenum pressure decreased to about half of peak pressure due to the closing of an oxidizer feed valve. Fuel plenum pressure at the same time, however, was kept to about 70% of peak pressure. Therefore, it is thought that the equivalence ratio increased significantly, and energy due to combustion also became lower. The fact that the combustion chamber pressure decreased with oxidizer plenum pressure can describe same thing. They led to a weaker leading shock wave and unstable propagation. As a result, the rotation direction changed.

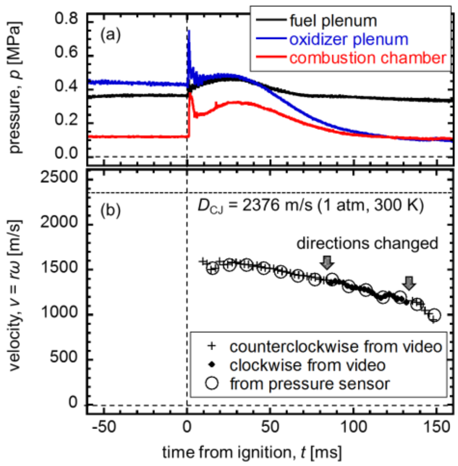

Fig. 7 Time history of the plenums and combustion chamber pressure (a) and velocity (b) from the self-luminescence visualization experiment

Fig. 8 shows a high-frequency pressure profile of the self-luminescence visualization experiment obtained from the pressure sensor. As can be seen in Fig. 8(a), a rise in pressure was observed at even intervals, and the detonation wave propagated stably. Fig. 8(b) shows 1 cycle of the pressure profile with superimposed images from the self-luminescence visualization experiment. Actually, the images and pressure profile have a half-cycle of lag, because in the true synchronized images, there was not a clear detonation wave due to the luminescence of the grease on the pressure sensor. Therefore, the pressure profile and images were superimposed assuming the velocity was perfectly constant. Images were cut out and lined up. Since the framing interval was finite, synchronization uncertainty was as much as the width of an individual image. Unfortunately, it was difficult to compare the combustion chamber and plenum pressure and to discuss the stop/start of fuel and oxygen injection due to the 10-mm distance between the pressure port and injector exit, and the detonation wave was propagated above the outer edge of the combustion chamber, as shown in Fig. 5. That raised the pressure difference between the pressure port and the outer edge of the combustion chamber.

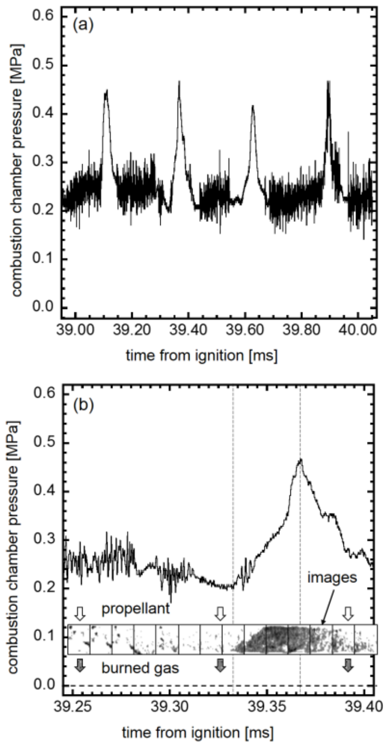

Fig. 8 Combustion chamber pressure profile with superimposed images from the self-luminescence visualization experiment

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

a) papers published in peer-reviewed journals,
   1) S. Nakagami, K. Matsuoka, J. Kasahara, Y. Kumazawa, J. Fujii, A. Matsuo, I. Funaki, Experimental Visualization of the Structure of Rotating Detonation Waves in a Two-Parallel-Plane Combustor , Journal of Propulsion and Power (accepted).

b) papers published in non-peer-reviewed journals or in conference proceedings,
   1) S. Nakagami, K. Matsuoka, J. Kasahara, Y. Kumazawa, J. Fujii, A. Matsuo, I. Funaki, Structure of Rotating Detonation Waves in a Two-Parallel-Plane Combustor with Orthogonally Mixing Injectors, AJCPP2016-155, Asian Joint Conference on Propulsion and Power, March 16-19, 2016, Sunport Hall Takamatsu, Kagawa, Japan.
   2) S. Nakagami, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, Schlieren-System-Visualization of Combustion Phenomena in a Two-Parallel-Plane Combustor, Propulsion and Energy 2015, 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA 2015-4102, July 27-29, 2015, Orland, Florida, USA.